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LESSONS FROM BUILDING LASER-DRIVEN FUSION IGNITION TARGETS WITH THE PRECISION ROBOTIC ASSEMBLY MACHINE

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The Precision Robotic Assembly Machine was developed to manufacture the small and intricate laser-driven fusion ignition targets that are being used in the National Ignition Facility. The machine enables one person to assemble a high-quality precision target in one day with repeatable quality. The target assembly technician provides top-level control of the machine, initiating and controlling the movement of the motorized precision instruments. Hand movements are scaled to precision at the 100-nanometer level. Sensors embedded in the manipulator system provide 100-mg resolution force and gram-millimeter resolution torque feedback of the contact loads between delicate components being assembled with micrometer-level or no clearance. Combining precision motion control with force and torque feedback provides active compliance for assembling tight-fitting or snap-together components. The machine provides simultaneous manipulation of five objects in a 1-cubic-centimeter operating arena, and can stitch together multiple millimeter-scale operating arenas over distances spanning tens of centimeters with micrometer-level accuracy. Technology developed with the machine has been migrated to other machines used to assemble fusion targets.

Keywords: *target fabrication, precision motion control, active compliance*

I. INTRODUCTION

The Precision Robotic Assembly Machine [1, 2, 3] is being used to manufacture laser-driven fusion ignition targets for the National Ignition Facility (NIF) [4, 5, 6]. The National Ignition Campaign (NIC) [7] goal of using the NIF to produce a self-sustaining nuclear fusion burn with energy gain requires targets that are demanding in materials fabrication, machining, and assembly. The NIC needs at least one target per day, and requires a target fabrication enterprise that readily accommodates changes in the design of the targets. The Precision Robotic Assembly Machine, shown in **Figure 1**, enables that production rate, and its reconfigurable nature has already accommodated changes to the target design. The machine is the first fully engineered system for assembling targets for the NIF, and its use has mitigated the risk to fusion ignition experiments posed by targets of variable quality. The machine provides unprecedented accuracy and efficiency, and provided the needed transformation in how fusion targets are assembled with a demonstrated ten-fold reduction in manpower needed to assemble a target and improved and repeatable target quality.

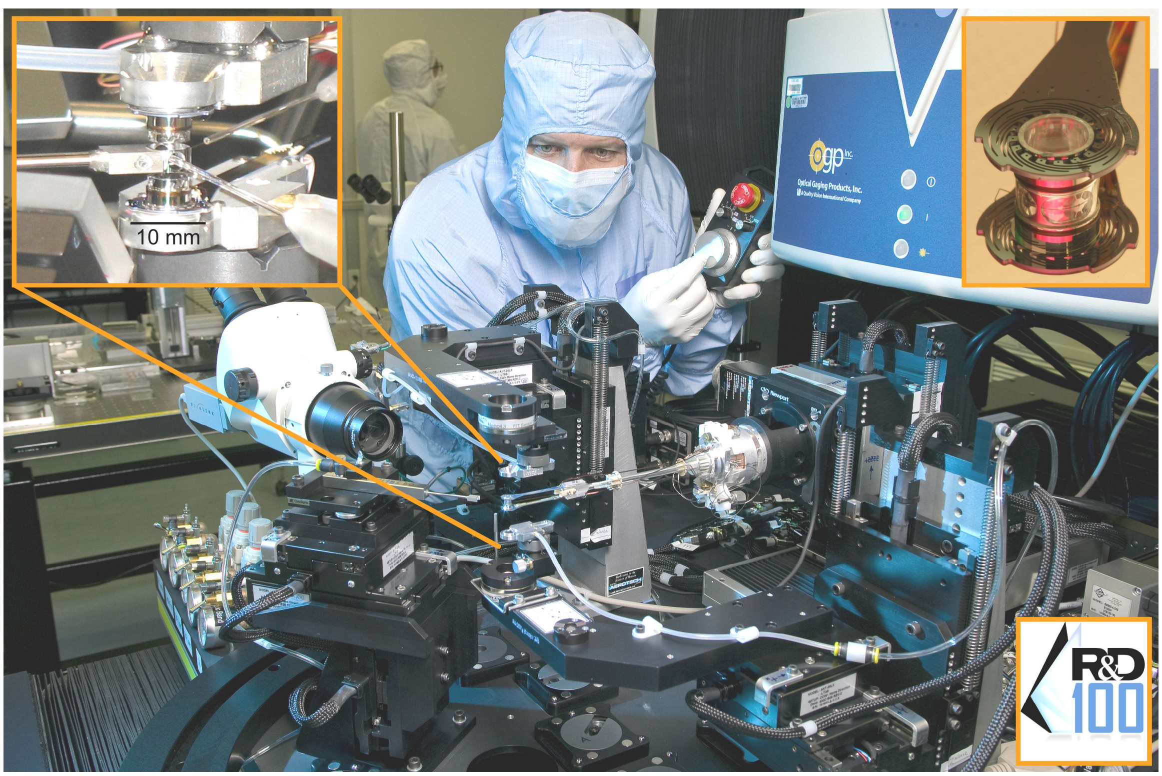

Fig. 1. The Precision Robotic Assembly Machine releasing a laser fusion target that was just assembled. (left inset) Target components being assembled. (right inset) A completed target.

Historically, building laser fusion targets depended on a significant amount of hand-crafting skill and technique involving microscopes and manually driven fixtures. A target, like the one shown in **Figure 2**, consists of millimeter-scale components assembled with micrometer-level accuracy. The target is designed so that the physics package (gold hohlraum inner-liner, fuel-filled capsule, and the gas between them) can be tailored independently of the thermal-mechanical package (TMP) that holds it (the TMP-halves, diagnostic band, and cooling arms). Many of the target components are designed to slip-fit together with micrometer-clearances, and the dimensional accuracy of a fully assembled target is in the range of 2–25 micrometers.

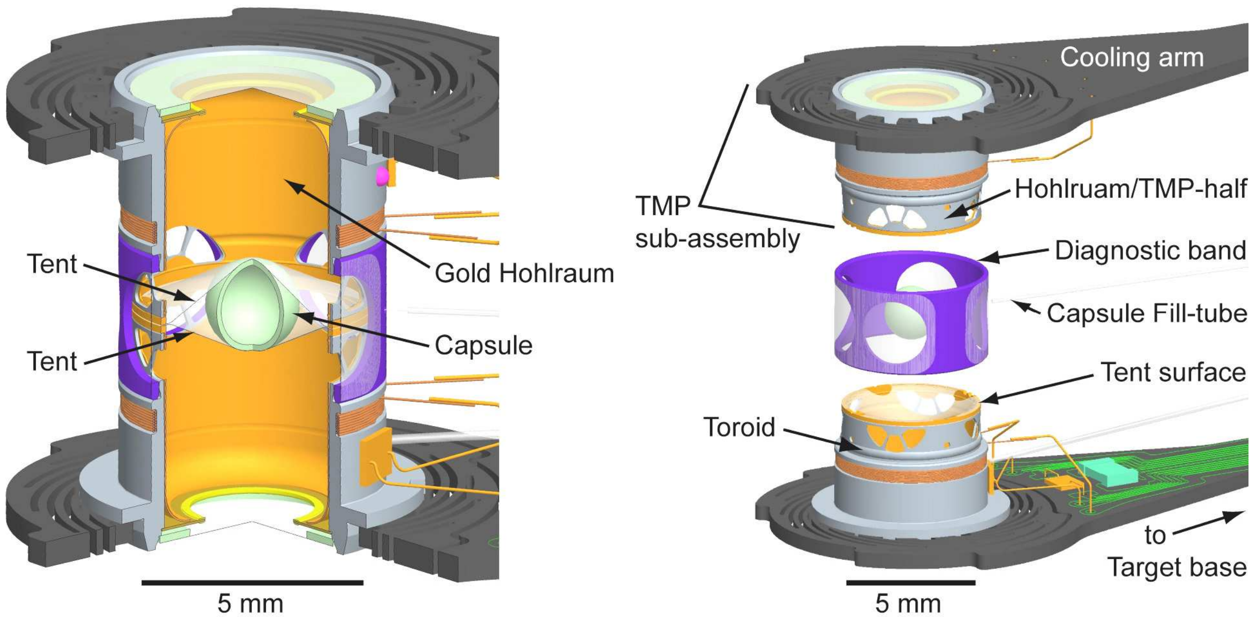

Fig. 2. Model of a fusion ignition target showing the major components.

II. OVERVIEW OF THE MACHINE

During its inception, the vision for the machine was to create a system that would allow a target assembly technician to build a target in a manner similar to how a surgeon uses a surgical robot to perform a delicate operation. The operator provides top-level control of the machine, initiating and controlling the movement of motorized precision instruments. In addition to using information provided by a machine vision system, innovative use of force and torque feedback allows manipulating the delicate components when they are in contact with each other. The combination of precision motion control with high resolution force and torque feedback provides the operator active compliance when assembling delicate components. The operator controls the contact loads by adjusting the displacement of the components. This approach avoids the complex passive compliant elements that would be needed if the delicate target components had to self-align while being manipulated by stiff, displacement-based motorized stages.

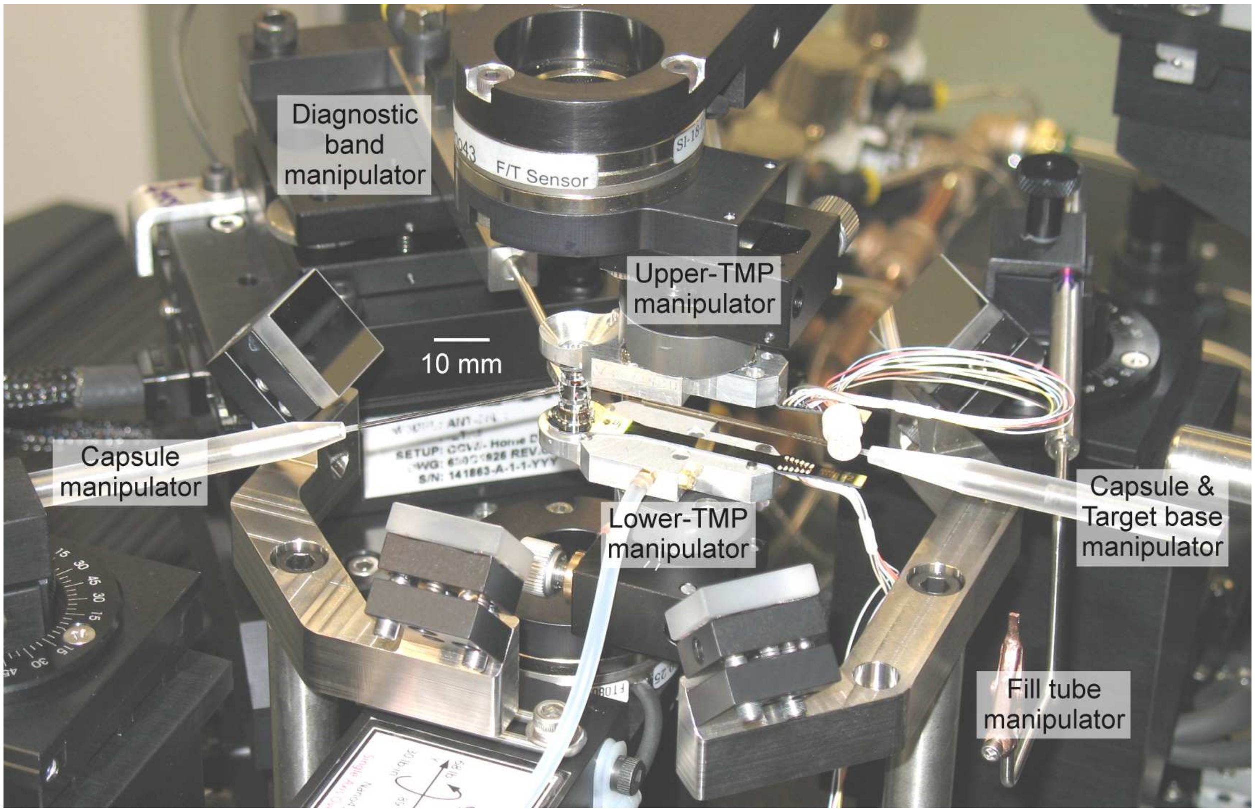

Fig. 3. Close-up view of the operating arena in the manipulator system, with a target being assembled.

The Precision Robotic Assembly Machine operates in a class 100 clean room, and consists of an LLNL-developed manipulator system integrated with an optical coordinate-measuring machine. **Figure 3** shows a close-up view of the manipulator system, which can be reconfigured to accommodate different target designs or assembly procedures. Nineteen motorized and ten manual degrees of freedom provide simultaneous manipulation of five objects in a 1 cubic-centimeter operating arena with 100-nanometer repeatability (precision) and micrometer accuracy. Sensors in the manipulator system provide 100-milligram resolution force and gram-millimeter resolution torque feedback of the contact loads between components being assembled with micrometer-level or no clearance. The optical coordinate-measuring machine (OCMM) has a machine-vision system with edge-detection algorithms, a laser-based distance-measuring probe, and an optional touch-probe [8, 9]. The OCMM provides 3-micrometer measurement accuracy in the 15 cm x 30 cm x 15 cm work volume for a target and its base.

Target components are held by a vacuum chuck at the distal end of tooling that attaches that component to its manipulator. Incorporated in the proximal ends of the tooling are kinematic or semi-kinematic mounts that provide accurate remove-and- replace orientation of the tooling. A relatively open operating arena is maintained by using kinematic mounts on the capsule manipulators and on auxiliary mirrors that provide the OCMM with multiple horizontal-direction view-lines into the arena. This allows those systems, and the target base, to occupy the same regions at different times during the assembly process. Additional remove-and-replace systems include a long working-distance binocular microscope with an integral video camera, and a steady-rest that assists the hand-application of adhesive used to hold the target components together.

The vision and measurement systems of the OCMM are used to guide the initial approach and alignment of the target components, and to measure the relative position and orientation of the components. The force and torque feedback is used to guide the final approach, alignment, and mating of the delicate target components. The OCMM's working volume of 61 cm x 66 cm x 30 cm allows the Precision Robotic Assembly Machine to stitch together multiple millimeter-scale operating arenas, over distances spanning tens of centimeters, with micrometer-level accuracy.

An operator provides top-level control of the machine, responding to 100-milligram changes in contact forces by initiating and controlling the actions of the motorized instruments with hand movements scaled to precision in the 100-nanometer world. Adding a machine-based top-level control system would allow automating the assembly process. In its present configuration, the Precision Robotic Assembly Machine provides an appropriate balance between the earlier method of manually assembling a target and a fully automated system. Certain aspects of the target assembly process, such as alignment of components and measurements of that alignment, have been automated. Target designs and components continue to evolve and change during the NIC, with identical targets typically occurring in lot sizes of one to five. These changes are readily accommodated by having the target assembly technician provide top-level control of the machine. If targets for a campaign were identical to each other, or if the machine is adapted to build some other miniature system in high volumes, the trade-off between the investment needed to achieve a higher level of automation versus maintaining an operator-in-the-loop would favor adding a machine-based, top-level control system.

III. EARLY USE OF THE MACHINE

During the development of the machine, targets where being built with existing equipment, fixutes, and procedures. Lessons learned while building those targets motivated changes in the target design while the Precison Robotic Assembly Machine was being deployed. By design, the flexibility to accommodate such changes existed, and the first as-assembled configuration of the manipulator system and baseline procedure for using it were different from what was originally planned. Within a few weeks of deploying the machine, the target design changed again, necessitating another reconfiguration of the manipulator system. The most significant difference betwteen the first targets built by the machine and the ones that followed is how the capsule fill-tube assembly (CFTA) is assembled with the diagnostic band. In the first targets, the CFTA and diagnostic band were loaded onto the machine as separate components, and brought together on the machine. This required the diagnostic band to have a slot that allowed the CFTA's fill-tube to pass into the mid-plane of the diagnostic band. Although this initial target design was straightforward to assemble and had initial sucess, later targets of this design were not gas-tight when the target was at the cryogenic temperatures used to form the hydrogen fuel ice layer inside the capsule. This problem was solved by replacing the slot in the diagnostic band with a small hole that the fill-tube has to be threaded through. The new threaded diagnostic band design requires preassembling the CFTA and diagnostic band before mounting them on the machine. A video showing a target being assembled, along with highlights of the threading process, is available on the NIF web site [2]. The remainder of this section provides highlights of building the earlier non-threaded diagnostic band target with the machine.

Figure 4 shows the target components mounted to the vacuum chuck tooling on the Precision Robotic Assembly Machine in preparation for aligning the capsule-fill-tube assembly to the diagnostic band. The target (Figure 2) consists of an upper and lower half — referred to as TMP-halves — and a central portion consisting of the capsule, its fill-tube, and the diagnostic band.

The 2 mm diameter capsule has a fill-tube consisting of a 150 micrometer diameter polymer-coated glass tube connected to a 30 micrometer glass tube that tapers to 10 micrometer at the capsule connection. Referring to Figure 4, the capsule is initially held by the thin vacuum wand on the right, with the fill-tube threaded down the center of that vacuum wand. The second thin vacuum wand, exactly opposite the first one, is used to hand-off the capsule to the pedestal below it so that the capsule can be raised into the diagnostic band. Figure 4 also shows a horizontal-direction view captured by the vision system of the OCMM. A thin vertical-direction slot in the diagnostic band (not visible in the figure) allows the capsule-fill-tube assembly to be raised into the diagnostic band.

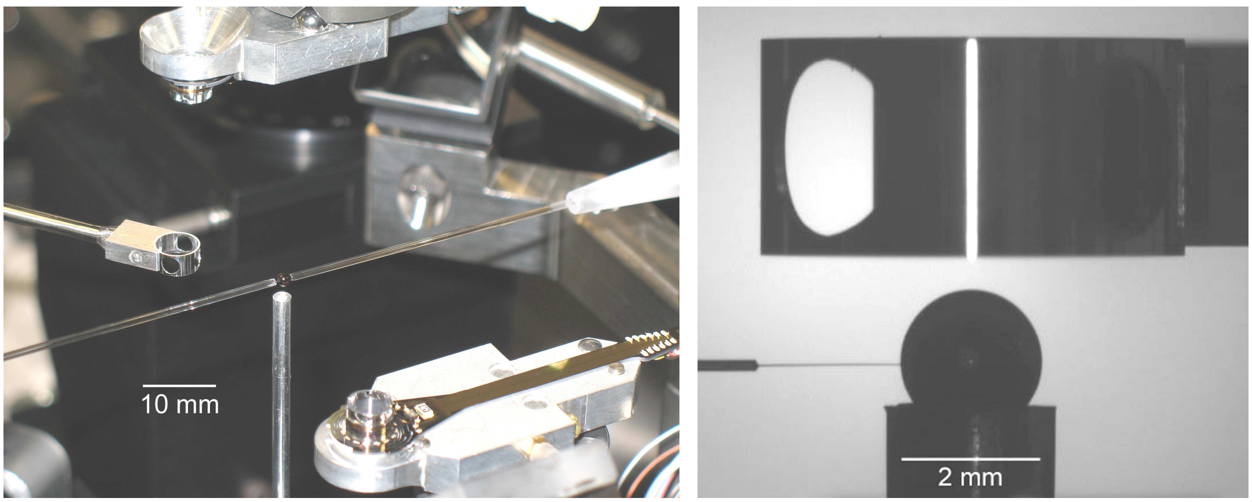

Fig. 4. (left) Target components mounted to the vacuum tooling on the Precision Robotic Assembly Machine in preparation for assembly. (right) Image from the OCMM vision system showing the capsule-fill-tube assembly ready to be raised into the diagnostic band.

Figure 5 shows the capsule-fill-tube assembly being aligned to the diagnostic band. The capsule is centered in the diagnostic band by manipulating the thin vacuum wand that holds the capsule, while the other thin vacuum wand supports the free end of the capsule fill tube. Figure 5 also shows the two TMP-halves positioned over the capsule and diagnostic band in preparation for “tenting,” which refers to the manner in which the capsule is held in a target assembly. Referring to Figure 2, a 100 nanometer thick polymer membrane (tent) is attached to the open end of each TMP-half. Each TMP-half is manipulated so that it is centered on the diagnostic band and capsule. When the two TMP-halves are brought together, the capsule is captured between the two tents and held in place by them.

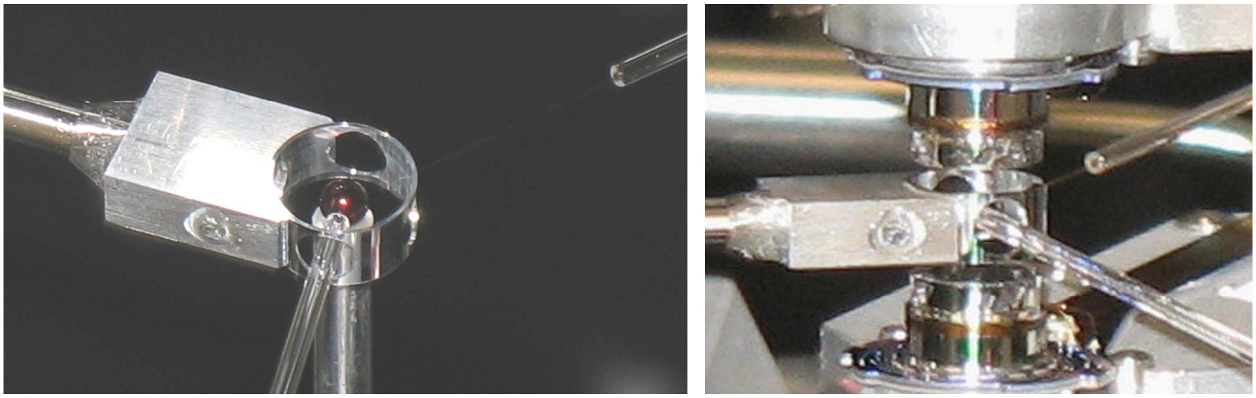

Fig. 5. (left) Capsule being centered in the diagnostic band. The thin vacuum wand on the right is supporting the free end of the capsule fill-tube. (right) Diagnostic band, capsule, and TMP-halves fully aligned and ready for tenting.

The tents can be seen in **Figure 6**, which shows a view along the target centerline of the fully aligned diagnostic band, capsule, and TMP halves, just before and just after tenting. The vacuum wand used to center the capsule is retracted during the tenting process. Referring to Figure 2, each TMP-half has a toroidal surface that engages the diagnostic band in a slip-fit with a radial clearance of 0–2.5 micrometers. This tight fit is used to register the two TMP-halves to each other, and sometimes is so tight that the components go together with a light press-fit. As the TMP-halves enter the diagnostic band, the operator uses the force and torque feedback while manipulating them laterally to minimize the unwanted cross-direction forces and torques, essentially "feeling" the parts together. Once the TMP-halves enter the diagnostic band the

Fig. 6. Images from the OCMM vision system of the fully aligned diagnostic band, capsule, and TMP halves (left) just before tenting, and (right) just after tenting.

vision system can no longer provide direct feedback of the clearance between the components. This is where the force and torque feedback provides its greatest advantage: providing information on the clearance and contact between components that “had looked” or “should be” lined up adequately. The force and torque sensors allow an operator to sense what cannot be seen — small clearances or contact between visually inaccessible surfaces — so that adjustments in alignment can be made before possibly damaging the components being assembled

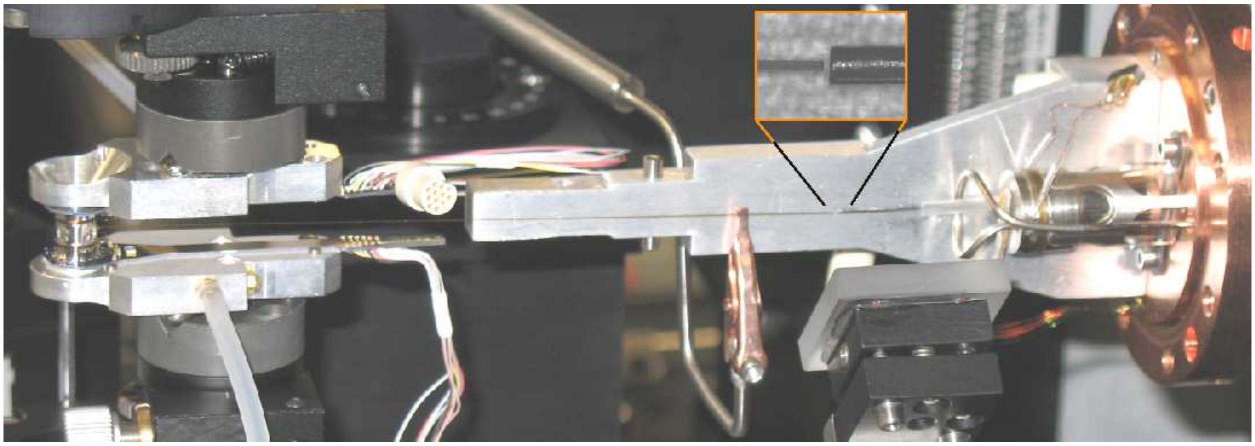

Fig. 7. Attaching the target to the target base. The free end of the capsule fill-tube is inserted into a metal tube in the target base. (inset) The close-up view shown in the inset is a horizontal-view image from the OCMM vision system.

Figure 7 shows the assembled target being aligned to the target base. The free end of the capsule fill-tube is manipulated so that it lines up with a metal tube in the target base. The auxiliary mirror shown in Figure 7 allows the downward-looking OCMM to be used to align the tubes in both a horizontal and a vertical plane. As the target base is moved to engage the ends of the cooling arms on the target, the glass fill-tube slides into the metal tube in the target base. To provide the necessary thermal conductance between the target and target base, the target’s cooling arms are clamped to the target base with indium shims and thermally conductive grease. With the shims and grease in place, the cooling arms fit onto the target base with a sliding fit. The shims and grease make it difficult to see micrometer-level or no clearance between the cooling arms and target base, so the operator uses the force and torque feedback to monitor and adjust the alignment between the components while attaching the target base. **Figure 8** shows the assembled target attached to the target base, with the vacuum chuck tooling for the TMP-halves retracted. The wires visible at the ends of the cooling arms connect heaters and temperature sensors on the target to electronic components attached to the target base.

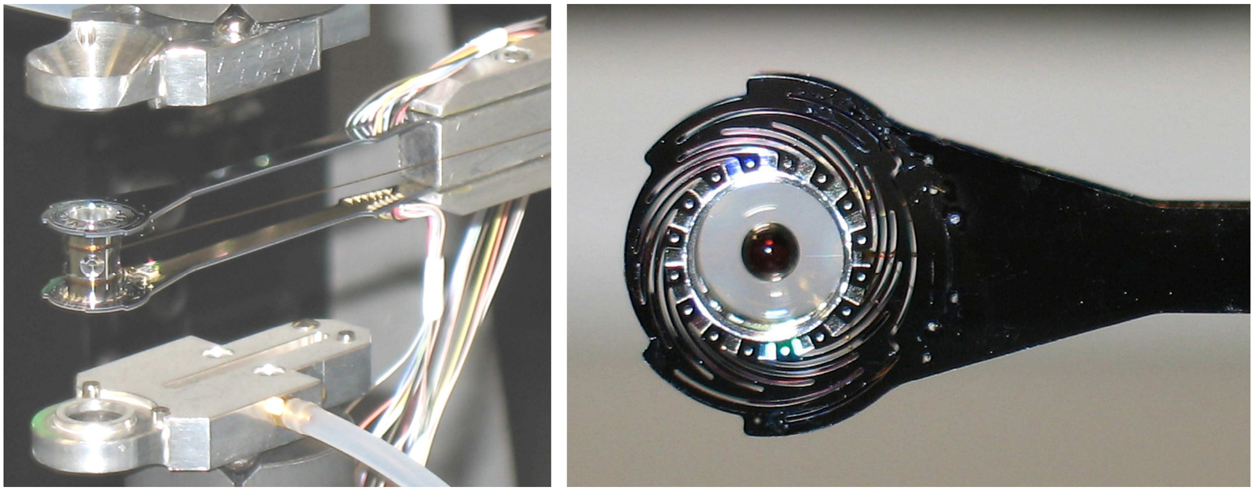

Fig. 8. (left) Target released from the vacuum chuck tooling and attached to the target base. (right) A view of the target showing the capsule suspended between the two tents.

IV. SUBSEQUENT DEVELOPMENT OF THE MACHINE

A strategy that guided the development of the Precision Robotic Assembly Machine was to create an expedited system that provided the functionality needed to enable a new and deterministic approach to building targets, while making provisions for functional upgrades that would address anticipated longer-term needs. Thirteen months after beginning the project, the manipulator system was used to build a target while using a microscope for the vision system instead of an OCMM. This allowed early testing of the strategy of using active compliance to assemble a target. Eighteen months after starting the project the manipulator system had been integrated with the OCMM, a full target meeting NIC specifications was built, and a process for using the machine was established. A month later NIC target production staff had been trained to use the machine, which became the baseline system for assembling targets. The remainder of this section describes some of the upgrades that occurred after that time.

One of the first upgrades to the machine was to add a steady-rest and long working-distance microscope to aid the hand-application of adhesive used to bond the assembled target. A temporary steady-rest and a microscope supported by a floor-mounted stand were used when building the first targets with the machine. This strategy expedited deploying a new machine for building targets sooner rather than later, and allowed determining the needed lines-of-sight and hand-support locations in the context of experience gained while building targets with the machine. In addition to aiding adhesive bonding operations, the microscope provides qualitative auxiliary views into the operating arena while aligning and assembling the target components, so it is usually present on the machine throughout the assembly process.

The manipulator system was initially integrated with a standard Quest-650 OCMM from Optical Gaging Products, Inc. [8, 9]. A 0.5x lens having a 130 mm working distance provided an acceptable trade-off between lateral resolution, maximum field of view, and working distance. However, that lens gets close to the manipulator system when using the horizontal-view mirrors to image the operating arena, creating the risk of a collision between the OCMM and manipulator system. The short-term solution for mitigating this risk was to relocate a limit switch that inhibits downward motion of the lens, so motion would stop before the lens reached the highest point on the manipulator system. A dead-man bypass switch was added to override that limit switch. During regular downward viewing into the operating arena with the OCMM, the operator did not have to be concerned with the dead-man switch or a collision. To move the lens below the safe height, the operator had to hold the dead-man switch closed. If the operator felt that a collision was imminent, letting go of the switch would stop the motion. The long-term solution for avoiding a collision between the OCMM and the manipulator system was to work with the OCMM vendor to produce a modified version of their standard system. The modified system uses a 0.45x lens having a 200 mm working distance, and the optical system is raised by 178 mm. The manipulator system was integrated with the modified OCMM in January 2010, and the vision system components now stay above the top of the manipulator system.

A safety feature retained from the initial execution of the machine is low over-current limits on the linear motors in the manipulator system. The linear motor driven slides derive their stiffness in the degree-of-freedom direction from the control system. The maximum force that the motor can produce is controlled by the limiting the motor current. If the instrument carried by a linear motor starts pressing against another object, or is pressed upon, the linear motor will push until a 10 N force is developed and then be electronically disabled and become a free mass. This makes the manipulator system forgiving when moving the instruments, target components, and mirrors within the operating arena.

A performance enhancement that was added to the taller OCMM, and then retrofitted onto the earlier standard OCMM, was the addition of the vendor's through-the-lens (TTL) laser-based distance measuring probe. The ability to make quick height measurements with a system that uses the vision system's lens — with the benefit of its long working distance — provided a significant advantage while setting up the manipulator system instruments and target components, and while assembling a target or inspecting a completed target. The system allows conveniently toggling between the vision system which provides XY-plane measurements of features identified by edge-finding algorithms, and the TTL laser probe which provides Z-height measurements of surfaces, while not significantly moving the OCMM relative to the manipulator system.

V. ENABLING TECHNOLOGIES

The combination of precision motion control with high resolution force and torque feedback provides the operator — whether a person or machine-based control system — active compliance when assembling delicate components. The use of real-time dimensional metrology allows deterministically aligning and joining components, and immediately verifying the accuracy of the completed assembly. Targets that used to take two to three people one week to build with previous equipment are now being routinely built by one person in one day. Technologies developed for this machine were migrated to other machines used to manufacture NIC fusion targets. The Flex-FAM [10] is a follow-on target assembly machine that utilizes the same real-time dimensional metrology and force and torque sensing as the Precision Robotic Assembly Machine. The Hohlraum Insertion Station [11] is used to preassemble certain target components, and was upgraded to use the same force and torque sensing. Completing the circle of technology proof-of-principle and propagation, next-generation tooling for assembling targets that was developed with the Flex-FAM has been adapted for use on the Precision Robotic Assembly Machine.

Laser-driven fusion targets for the NIF are a first application for the Precision Robotic Assembly Machine, which can be adapted to build other complex miniature systems. The multiple technologies integrated into the machine bridge the gap between building miniature- and man-sized machines. The machine could provide a key enabling platform for significant advances in the discovery and manufacture of centimeter-scale systems that integrate millimeter- and micrometer-scale optical, electrical, mechanical, and biological subsystems. Examples include medical devices for minimally-invasive surgery, data storage and communication devices, microfluidic devices for testing and diagnostics, and ever miniaturized sensors and actuators in vanishingly small systems. Migrating the synthesis of technologies demonstrated by the machine into the field of teleoperated systems would allow an operator to perform precision motion control with tactile feedback in applications involving remote or hazardous operating arenas.

VI. CONCLUSIONS

The Precision Robotic Assembly Machine transformed the way laser-driven fusion ignition targets are built, enabling one person to assemble a high-quality target in one day, and repeat that quality every time. The vision was to create a system that would allow a target assembly technician to build a target in a manner similar to how a surgeon uses a surgical robot to perform a delicate operation. The operator provides top-level control of the machine, initiating and controlling the movement of the motorized precision instruments. Hand movements are scaled to precision at the 100-nanometer level, and sensors embedded in the manipulator system provide 100-mg resolution force and gram-millimeter resolution torque feedback of the contact loads between the delicate components being assembled. Combining precision motion control with force and torque feedback provides active compliance for assembling tight-fitting or snap-together components. The machine provides simultaneous manipulation of five objects in a 1-cubic-centimeter operating arena, and can stitch together multiple millimeter-scale operating arenas over distances spanning tens of centimeters with micrometer-level accuracy. The machine has enabled every operator to build fusion targets with an equally high level of finesse and repeatability, and technology developed with it has been migrated to other machines used to assemble NIC targets.

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